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MODELING OF THE NON-AUDITORY RESPONSE TO BLAST OVERPRESSURE

Computer Model of Complex Waves Within an Enclosure and Their Biological Effects

ANNUAL/FINAL REPORT

William Roush
James H. Stuhmiller

JANUARY 1990

Supported by

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The repeated passage of pressure waves past a given point, following an explosion in an enclosure, results in the long and complicated pressure time histories called "complex waves." The waves are not only complex because of their temporal variation, but their effect on biological structures depends on the *direction* of each wave component. The ability to estimate injury under these circumstances represents one of the greatest challenges of biomechanical modeling.

A mathematical model for the reflections of blast waves within an enclosure has been constructed based on the concept of mirror-like reflections of the wave front at each solid surface. The model accounts for the position and orientation of each surface and allows for the presence of openings, such as doors and windows. A simplified model for the venting of explosion product gases is also included.

The pressure loading time histories are combined with simplified models of the structural response of various organ systems that are known to be injured by air blast. The combined models not only allow estimates of potential injury due to explosions within enclosures, but also provide a means of judging the accuracy of the blast calculations in terms of the requirements of injury prediction.

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Computer Model of Complex Waves Within an Enclosure and Their Biological Effects

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The measured and calculated pressure histories are used in the simplified biological response models and a comparison made of the critical parameter of injury. For the tympanic membrane and the upper respiratory tract, the critical stress calculated using the mathematical model differ from that calculated using the measured data by an amount not significantly greater than the variation of stress as a correlate of injury. For the lung, however, the variations are much larger and suggest that a more accurate prediction scheme may be required.

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William Roush
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Applied Science and Engineering Technology
JAYCOR

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Computer models, Explosions, Pressure waves, Blast injury, weapons Effects
Biological, Complex Wave Model

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ILLUSTRATIONS

TABLE

1. INTRODUCTION

The repeated passage of pressure waves past a given point, following an explosion in an enclosure, results in the long and complicated pressure time histories called "complex waves." The waves are not only complex because of their temporal variation, but their effect on biological structures depends on the *direction* of each wave component. The ability to estimate injury under these circumstances represents one of the greatest challenges of biomechanical modeling.

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2. COMPLEX WAVE MODEL

The first step in COMPLX is to use the method of images[3,4] to generate a distribution of changes which produces the same wave pattern within the enclosure.

This algorithm produces reflected images of the blast source, creating N primary images (Fig. 1), where N is the number of enclosure walls. The primary images are reflected be the walls of the enclosure, creating $N*(N-1)$ secondary images (Fig. 2). Images do not reflect off the wall that created them. The secondary images reflect into the walls of the enclosure creating $N*(N-1)^2$ tertiary images (Fig. 3). This is an infinite process, producing reflecting images at increasing distances from the original source. The model carries out the process until the images reach a specific distance from the source. Images beyond this distance do not contribute to the pressure-time history during an interval equal to the maximum distance divided by the speed of sound.

First, the position of each image is computed as a function of the position of its source within the enclosure. The equations used for computing image positions are:

$$X_i = X_s - (2\, D_{surf}\, X_{norml})$$

$$Y_i = Y_s - (2\, D_{surf}\, Y_{norml})$$

$$Z_i = Z_s - (2\, D_{surf}\, Z_{norml})$$

where:

X_i = X coordinate of Image

Y_i = Y coordinate of Image

Z_i = Z coordinate of Image

X_s = X coordinate of Image source

Y_s = Y coordinate of Image source

Z_s = Z coordinate of Image source

X_{norml} = X component of the reflecting wall's unit vector

Y_{norml} = Y component of the reflecting wall's unit vector

Z_{norml} = Z component of the reflecting wall's unit vector

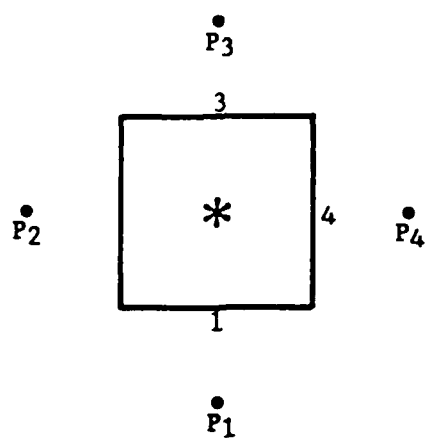D_{surf} = distance from the image source to the reflecting wall.

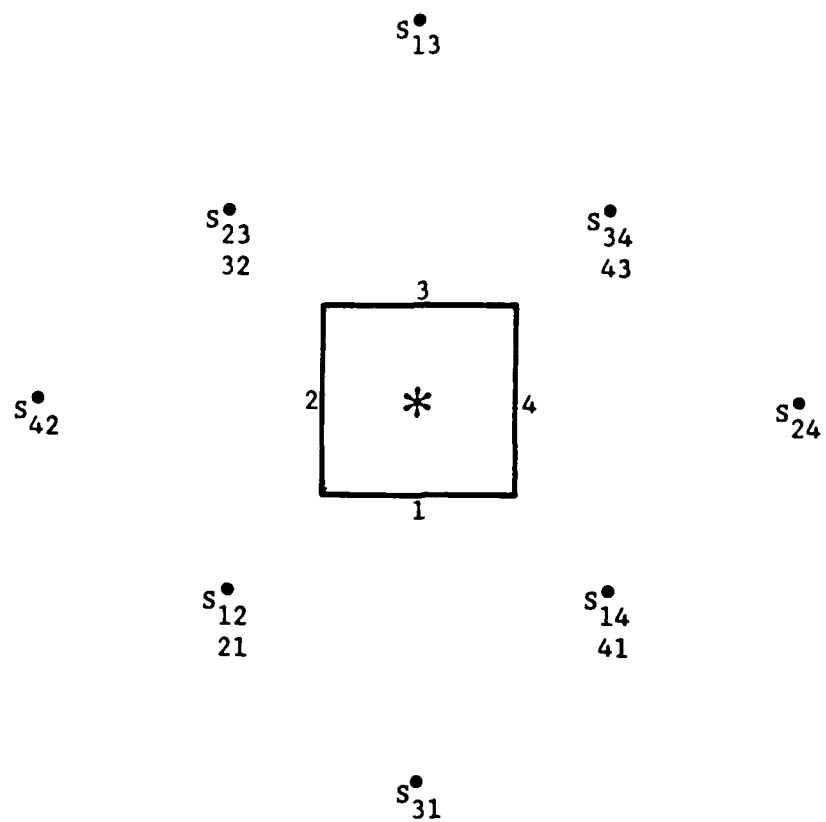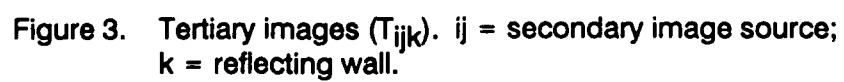Figure 1. Primary images (P$_i$). i = reflecting wall.

Figure 2.   Secondary images (S_{ij}). i = primary image source;
            j = reflecting wall.

T_{313}

T_{123}
213
132

T_{143}
413
134

T_{342}
432
423

T_{232}
434

T_{234}
324
243

T_{121}
323

3

2   *   4

T_{343}
141

T_{242}

T_{424}

1
T_{212}
414

T_{142}
412
421

T_{214}
124
241

T_{312}
231
321

T_{314}
341
431

T_{131}

Figure 3.   Tertiary images (T_{ijk}).   ij = secondary image source;
k = reflecting wall.

Next, the pressure-time history is computed as the sum of all blast waves that can be viewed at the sensor location of interest. The model computes the path from the sensor back to the original blast via each image and its source. For example, a tertiary image's path would involve the reflection of the blast off three walls (Fig. 4). COMPLX checks each path to determine if it can be "viewed" from the sensor, that is, that the path is not obstructed by any object and that the path intersects the reflecting wall. COMPLX creates a list of all paths that are in view of the sensor.

The pressure-time history is the sum of the individual blast waves, each of which is considered to be a Friedlander wave. The characteristics of the blast waves are calculated using the normalized blast parameters quoted in Chapter 6 of Baker.[5]

$$\text{Pressure-time history:} \quad P(t) = \sum_{i=1}^{k} P_i(t) \qquad 0 \le t \le T_{max}$$

where:

T_{max} is given by the maximum specified distance an image can be from the blast divided by the speed of sound.

i = blast wave index

k = number of blast waves seen by sensor

$$\text{Friedlander wave:} \quad P(t) = P_s \, (1 - t_a/t_d) \, e^{[-b(t_a/t_d)]}$$

where:

$P(t)$ = pressure at time t

P_s = peak pressure

t_a = time measured from wave arrival

t_d = positive duration of wave

b = exponential parameter of Friedlander wave

The parameters P_s, t_a, t_d, and b can be determined from Baker tables when the normalized distance from the sensor is known.
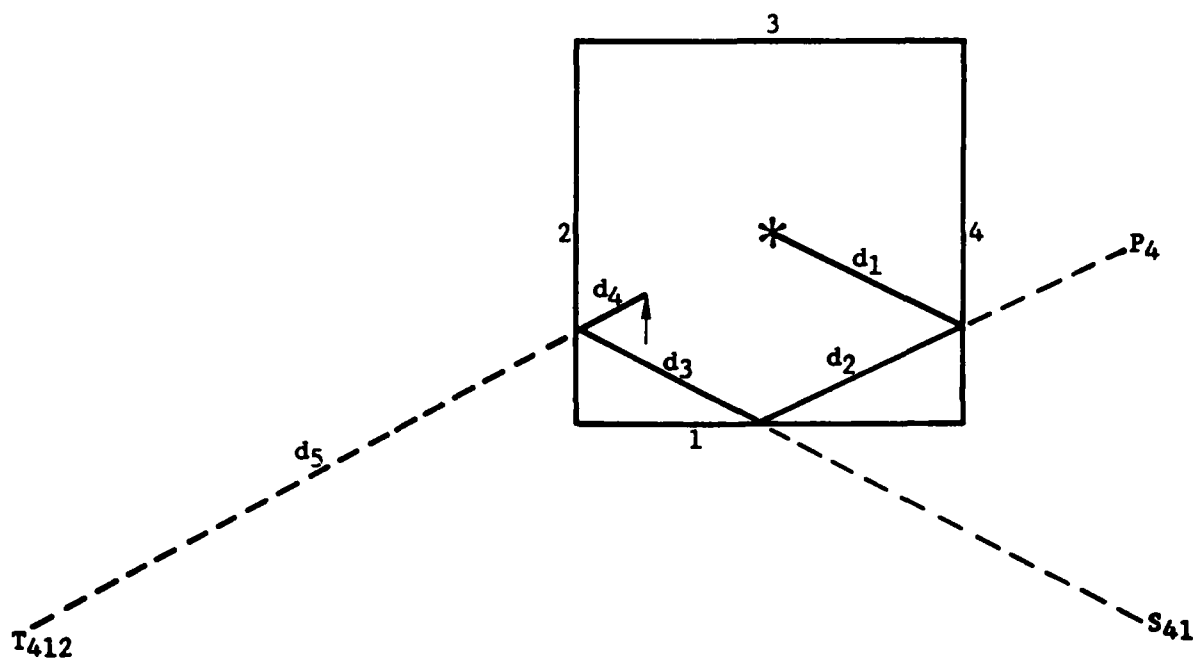
$$D_i = d/D_{not}$$

Figure 4. Third order reflection. The distance, d_5, between the sensor (1) and the tertiary image, T_{412}, is equal to the path of the blast wave, d_4, d_3, d_2, d_1.
($d_5 = d_4 + d_3 + d_2 + d_1$)

where:

D_i = normalized distance from source

d = distance of blast wave path

$D_{not} = (E/P_o)^{1/3}$

E = energy released by charge

P_o = ambient pressure

The blast parameters t and t_d are determined from the relations:

$t = T_a T_o$

$t_d = T_s T_o$

where:

T_a = normalized time of arrival

T_s = normalized positive duration

$T_o = D_{not}/a$

a = ambient speed of sound

The peak pressure, P_s, is determined both by the distance to and strength of the blast and the orientation of the incident wave to the sensor.

for $-\dfrac{\pi}{2} \leq \theta \leq \dfrac{\pi}{2}$

$P_s = [P_r \cos(\theta) + P_i \sin(\theta)] P_o R$

for $\theta > \left| \dfrac{\pi}{2} \right|$

$P_s = P_i [1 + 0.25 \cos(\theta)] P_o R$

where:

θ =   angle between the individual blast waves and the orientation of an object at the given location

P_s = normalized reflected pressure

P_i = normalized incident pressure

P_o = ambient pressure

R = reflectivity factor

The parameter R is the product of the reflectivities of each wall the wave encounters before reaching the sensor.

COMPLX adds the pressurization of the enclosure due to expanding gases of the blast to the pressure-time history. This corresponds to the "Quasi-Static Overpressure Response"[3] and "fill"[4]. The pressurization is the result of competition between heating of the ambient gases in the enclosure by the explosive and the loss of energy from the flow leaking out of the enclosure. The deviation for computing the pressurization of the enclosure follows as:

Equation of state for the entire enclosure:

$$pV = NRT$$

$$E = E_o + NC_v(T - T_o)$$

The explosion violently produces gas which adds mass and energy to the enclosure. Both factors increase the pressure of the enclosure:

$$\frac{dp}{p} = \frac{dE}{E} \qquad (1)$$

The explosion adds an amount of energy, E, when the explosion gases completely mix with the ambient gases,

$$E(t) = E_o + \Delta E \, \frac{V_E(t)}{V_R}$$

If the mixing proceeds at particle speed, u_e, behind the blast, then

$$\frac{V_E(t)}{V_R} = \frac{4/3 \; \pi(u_e t)^3}{4/3 \; \pi \; R_R^3} = \left(\frac{u_e t}{R_R}\right)^3 = \left(\frac{t}{T_e}\right)^3$$

where the volume, V, of the enclosure is represented by the equivalent sphere and T_e is the time for the expanding gases to fill the enclosure,

$$\frac{1}{E_o} \left(\frac{dE}{dt}\right)_e - \frac{\Delta E}{E_o} \frac{3}{T_e} \left(\frac{t}{T_e}\right)^2 \qquad \text{for} \quad t \leq T_e \qquad (2)$$

If there is a place for the gases to leak to the ambient, then the flow will take energy out of the enclosure at a rate

$$\left(\frac{dE}{dt}\right)_{out} = \frac{-E}{V} u_{out} A_{out} \qquad .$$

The flow is driven by the energy difference between the outside and the inside,

$$u_{out} - k\Delta p$$

so that

$$\frac{1}{E} \left(\frac{dE}{dt}\right)_{out} = - \left[\frac{k \ P_c \ A_{out}}{V}\right] \frac{\Delta p}{P_o} = \frac{1}{T_o} \left(\frac{\Delta p}{P_o}\right) \qquad (3)$$

T_0 depends on the effectiveness of the leak, where:

$T_0 = 0$ for a closed enclosure

$T_0 = \infty$ for a free field.

Combining Eqs. (1), (2), and (3) gives

$$\frac{d}{dt} \left(\frac{\Delta p}{P_o}\right) + \frac{1}{T_o} \left(\frac{\Delta p}{P_o}\right) - \left\{ \begin{array}{ll} 3/T_e \left(\frac{\Delta E}{E_o}\right)\left(\frac{t}{T_e}\right)^2 , & t/T_e \leq 1 \\ \\ 0 \quad , & t/T_e > 1 \end{array} \right\} \qquad (4)$$

Eq. (4) can be written in terms of dimensionless variables.

$$\left(\frac{\Delta p}{P_o}\right) - \left(\frac{\Delta E}{E_o}\right) f(t/t_c) \qquad (5)$$

where

$$\tau - t/t_e$$

to yield

$$\bar{p}' + \theta\bar{p} = \begin{cases} 3\tau^2 & , & \tau \leq 1 \\ \\ 0 & , & 1 < \tau \end{cases} \qquad (6)$$

where

$$\theta = \frac{T_e}{T_o} \quad .$$

The solution is then

$$\bar{p}(\tau) = \begin{cases} 3/\theta^3 \left[(\theta\tau)^2 - 2(\theta\tau) + 2 - 2\ e^{-(\theta\tau)} \right] & , & \tau \leq 1 \\ \\ 3/\theta^3 \left[\theta^2 - 2\theta + 2 - 2\ \exp^{-\theta} \right] e^{-\theta(\tau-1)} & , & 1 < \tau \end{cases} \qquad (7)$$

Using the equations of state, the equation for the expansion pressure becomes

$$p_e(t) = E_e/V_r \ f(\epsilon)$$

where:

E_e = energy of explosive

V_r = volume of enclosure

The final step in computing the load pressure-time history is to add the pressurization of the enclosure,

$$p(t) = p(t) + p_e(t)$$

3. ORGAN RESPONSE MODEL

COMPLX uses the load pressure-time history determined in the previous section as the driving force for the Generalizable Model.[2] The Generalizable Model[2] uses the damped harmonic oscillator equation for computing the structural dynamics of the body due to a blast wave. Therefore the equation of motion for the body becomes:

$$m \frac{d^2x}{dt^2} + \left(\frac{2m}{t_c}\right) \frac{dx}{dt} + kx = p(t)$$

where:

m = mass/area

t_c = characteristic damping time

k = spring constant/area

x = displacement

By solving for the displacement, x, and the velocity, dx/dt, COMPLX can compute the delivered stress to a particular organ. The model uses the displacement to compute the stress delivered to the tympanic and larynx membranes and the velocity to compute the stress delivered to the lung.

For the tympanic and larynx membranes, the stress is computed from:

$$\sigma_{tissue} = fkx$$

For the lung, the tissue stress is assumed to be proportional to the parenchymal pressure at the pleural surface, which is given by:

$$P_p = \frac{2m}{t_c} \frac{dx}{dt} \quad .$$

When the maximum tissue stress within an organ exceeds a critical value, injury is predicted to occur. Table 1 gives the parameter values for the organ systems.

Table 1. Parameter Values for the Three Organ Systems

Organ	m (kgm/m^2)	t_c (ms)	k (kPa/mm)	f	σ_{crit} (MPa)
Tympanic membrane	0.2	10	7.9	133	7.5-15
Upper respiratory tract	10	100	4	5	1
Lung	15	10	0	--	--

4. COMPARISON OF COMPLEX WAVE MODEL WITH DATA

We compare the predictions of COMPLX with two sets of complex blast environment data. The first set was measured inside an APC (Fig. 5). The second was measured inside a field bunker (Fig. 6). The digitized field data is plotted as a pressure-time history curve for comparison with the same curve produced by the model.

Since the exact conditions of the test are not known, the comparisons are only approximate but are intended to give the reader an idea of COMPLX's ability to predict the characteristics of a complex wave. In the following sequence of plots, for both the APC and the bunker data, the parameters of the model are set up such that:

1. Sensor positions and orientations are identical to those of the field blast.

2. The orientation function is the same as described in the second section of this report.

3. The walls have 100 percent reflectivity.

4. The enclosure is not pressurized.

The APC data was measured from a series of blasts in which the explosive charge weights were varied. The specific charge weights were 57 gm, 113 gm, 227 gm, and 454 gm. The pressure sensors (Fig. 5) used to measure the data were kept in the same location for the entire blast series. The N and S pressure sensors faced upwards while the Lambdroid's four sensors faced towards the blast, away from the blast, and perpendicular to the blast. The charges were all detonated in the center of the APC. Comparison plots have been made with all the APC data. Figure 7 is an example from this set.

The bunker data was measured from a series of blasts in which the sensor's position (Fig. 6) was varied. In addition, for each sensor position a different charge weight was detonated, 227 gm and 454 gm. The sensor configuration (Fig. 6) for this series of blasts was a free field pointing upward, Lambdroid with a sensor pointing towards the blast, a sheep with a skin sensor pointing towards the blast, and another sheep with an esophagus sensor. Comparison plots have been made with all Bunker data. Figure 8 is an example from this set.

We have taken peak pressure and total impulse from each of the comparison data sets and plotted field data versus model calculation (Figs. 9 & 10). This creates a scatter plot such that those points which lie on the 45 degree line are of equivalent values for field data and model calculation. The points that don't lie on the 45 degree line are off by a percentage difference. Scatter plots are a good means of visualizing the correlation of a large data set.
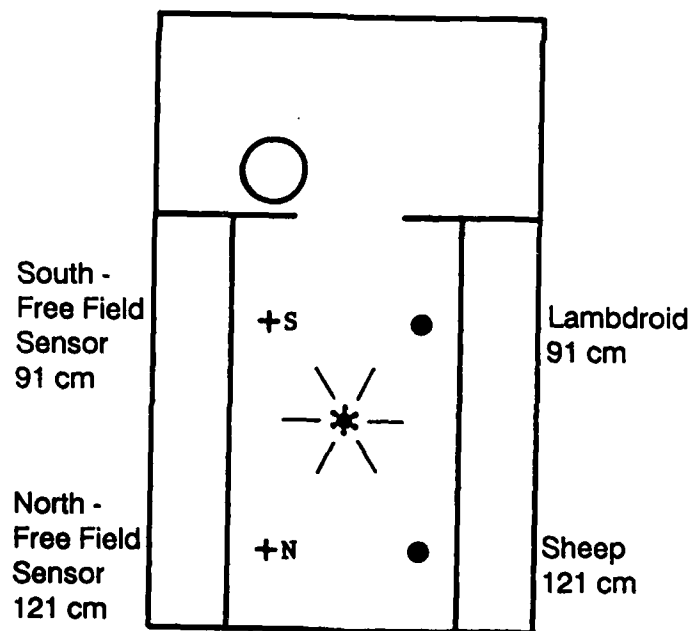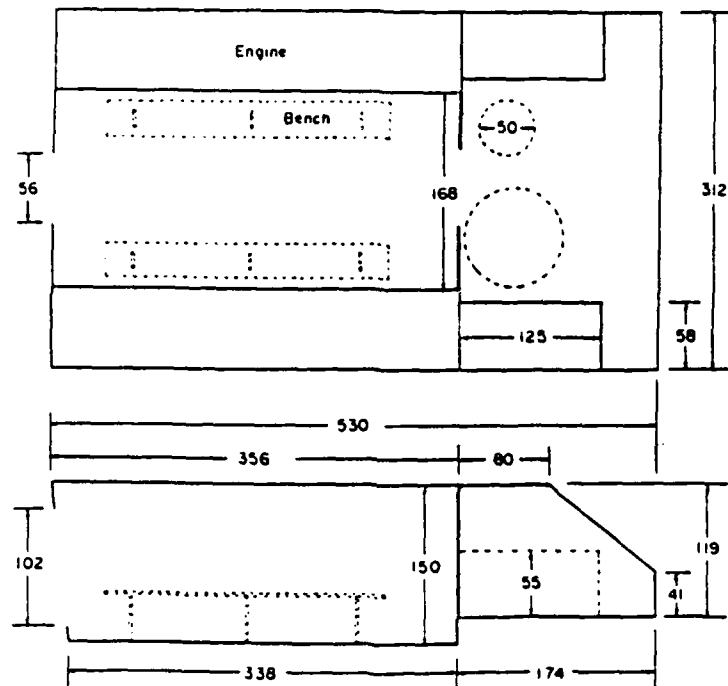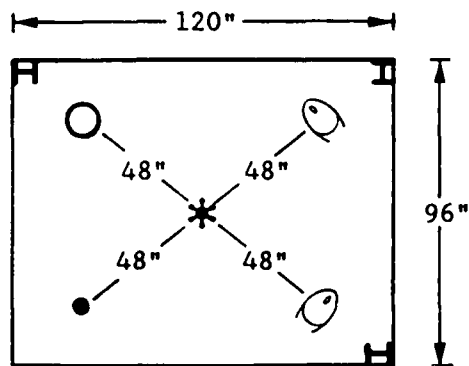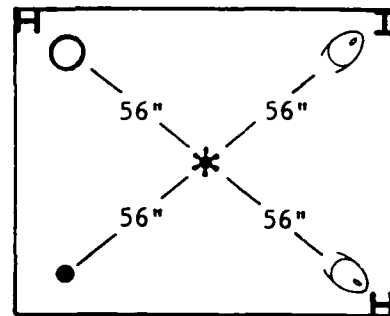
Figure 5.   APC specification and sensor location.
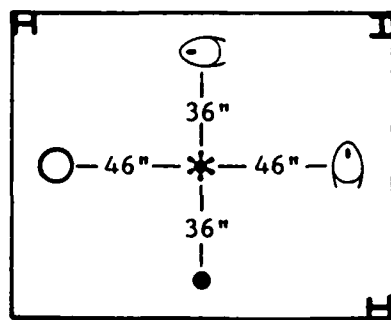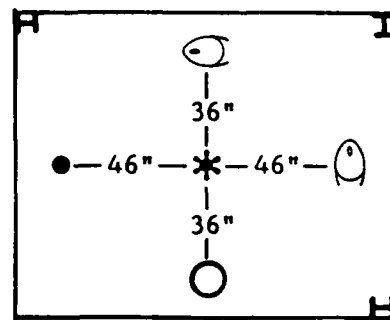
Figure 6.   Bunker specification and sensor location.
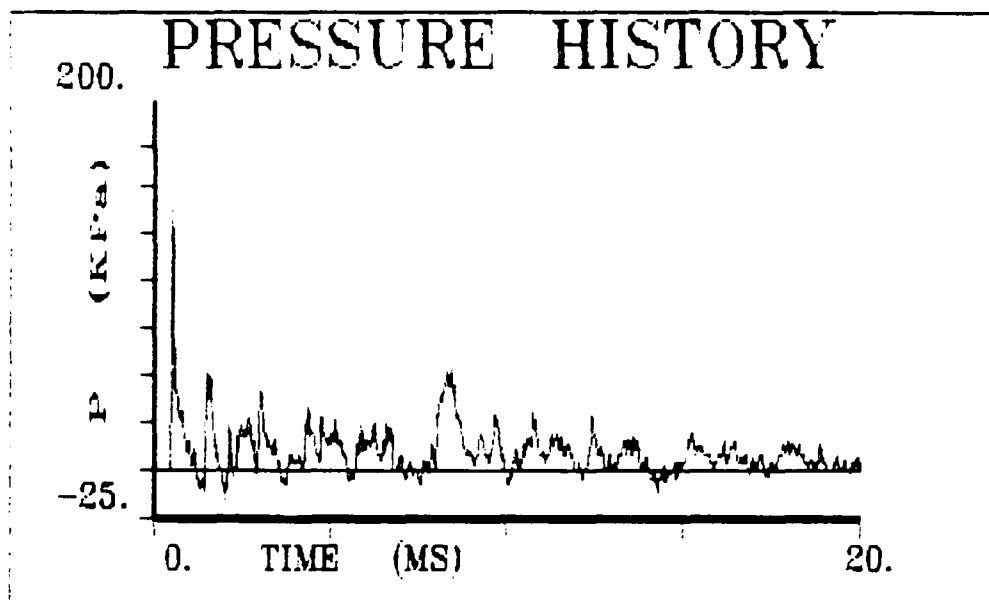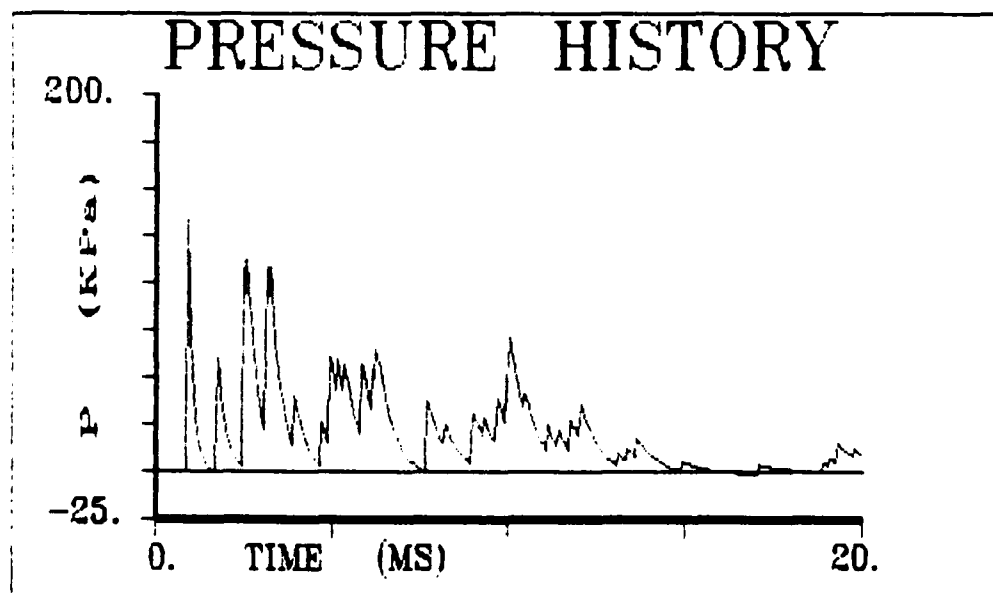
Field Data

Model

Figure 7. 57 gm C-4 blast "S" free field sensor.

PRESSURE HISTORY

1000.

P (KPa)

−100.

0.   TIME   (MS)   20.

Field Data

PRESSURE HISTORY

1000.

P (KPa)

0.   TIME (MS)   20.
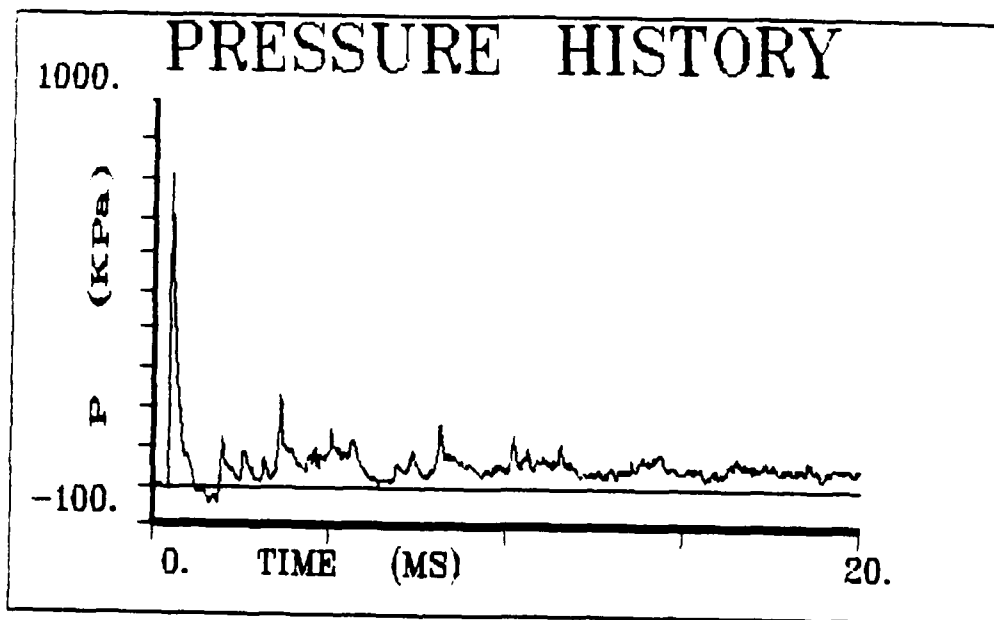
Model

Figure 8.   2/13/87 blast Lambdroid face-on sensor.

4-5
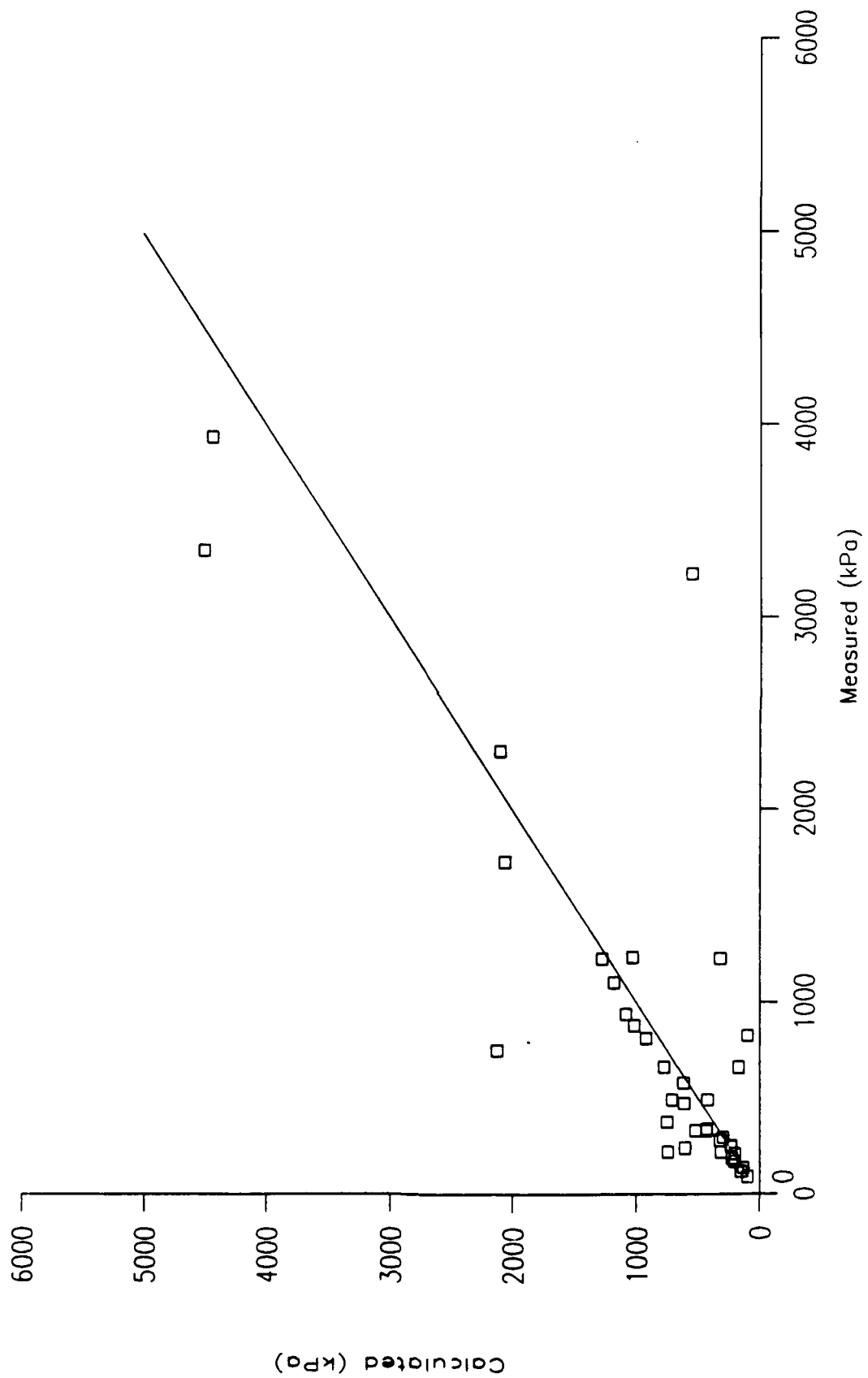
Figure 9. Peak pressure.
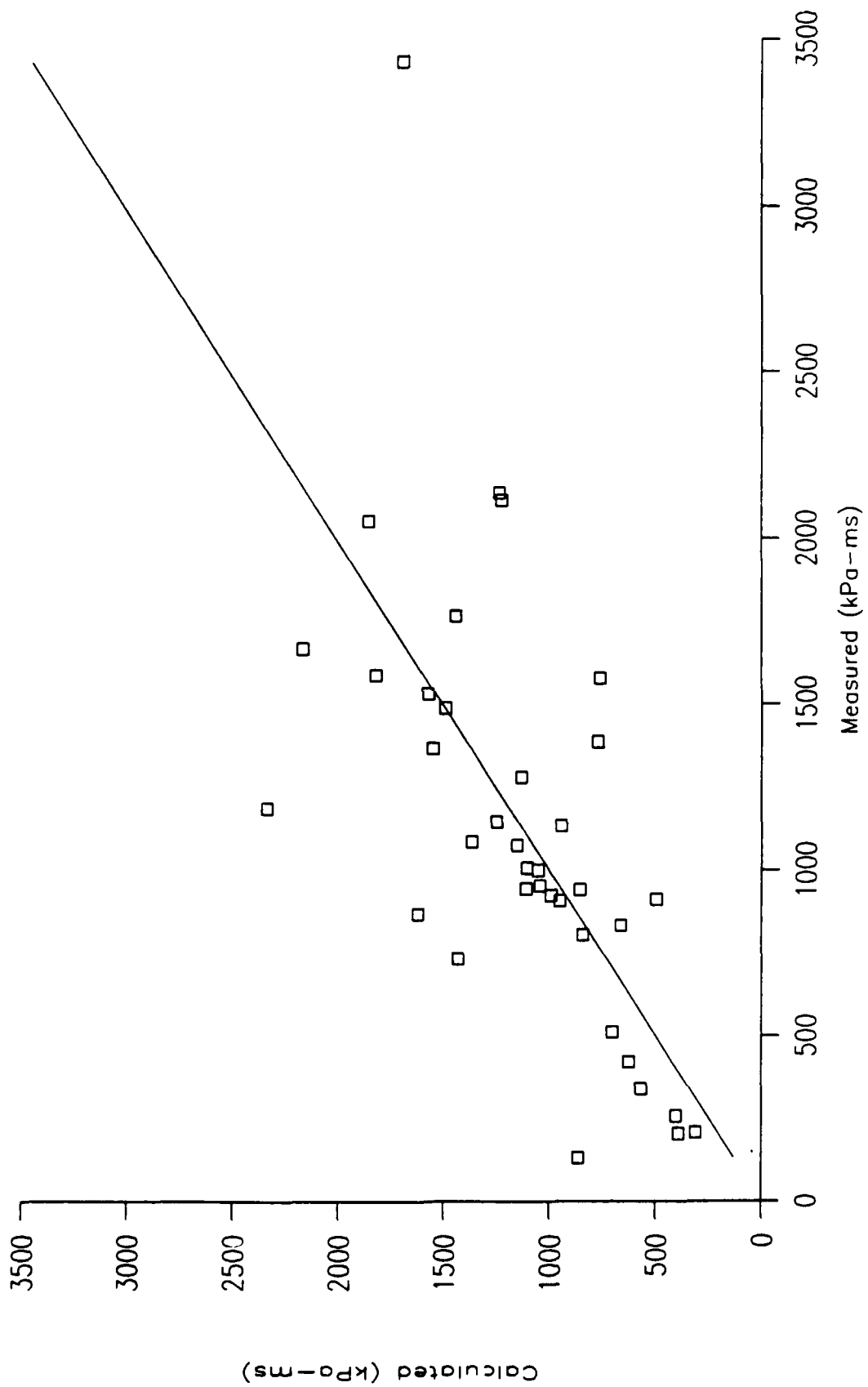
Figure 10. Total impulse.

5. COMPARISON OF ORGAN RESPONSE USING CALCULATED AND MEASURED PRESSURES

Both the predicted and measured pressure-time history curves are used as input to the Generalizable Model[2] to produce a sequence of three plots. The first plot graphs the maximum tympanic membrane stress as a function of time. The second plot graphs the maximum larynx stress as a function of time. The third plot graphs the lung's overpressure as a function of time. These quantities are used in the prediction of blast injury.

Figures 11 and 12 are the predicted organ response where the driving forces are plotted in Figures 8 and 9, respectively. Scatter plots have been made for the maximum tympanic stress (Fig. 13), the maximum URT stress (Fig. 14), and the work done on the lung (Fig. 15). A case-by-case description may be found in a supplementary report.
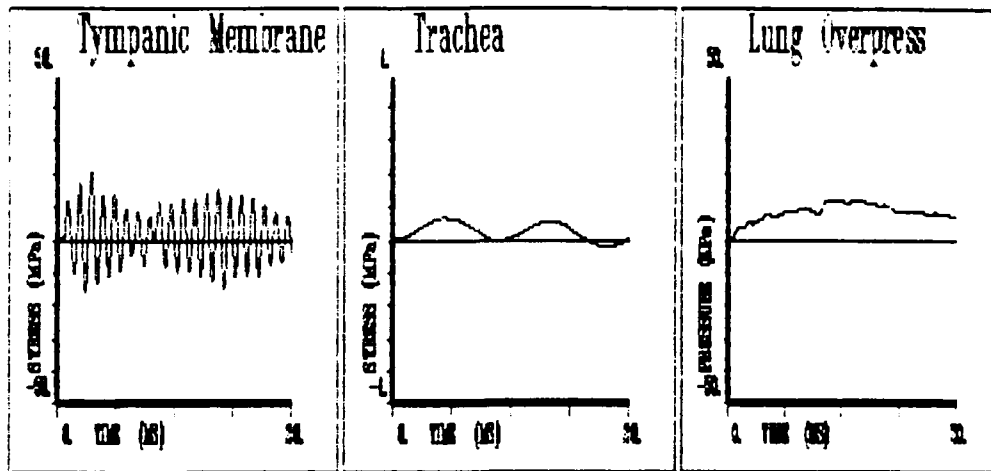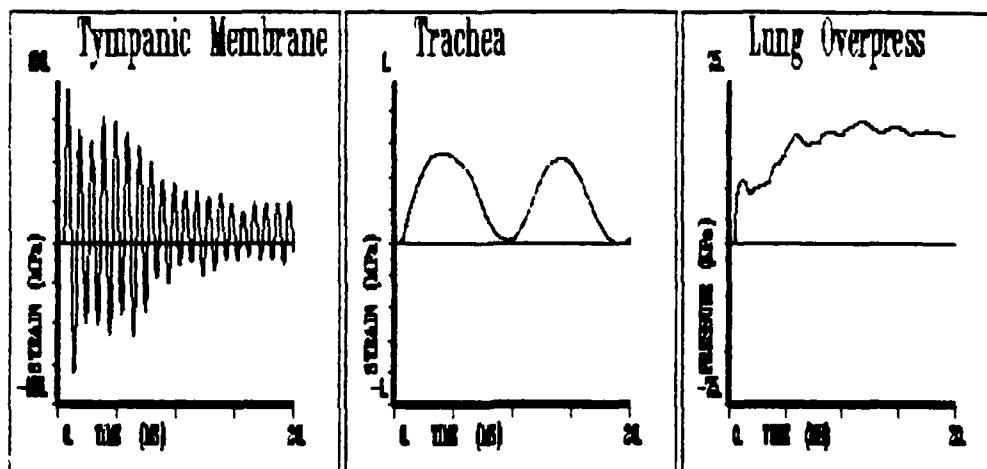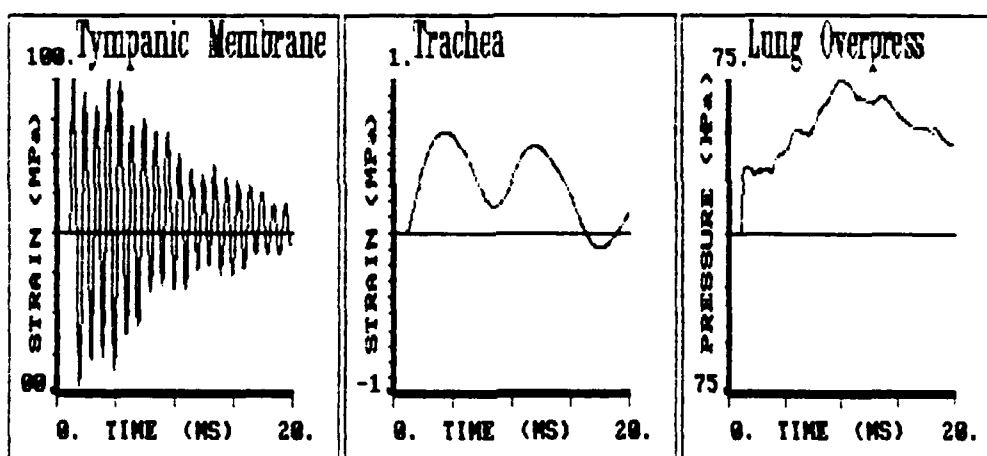
Field Data
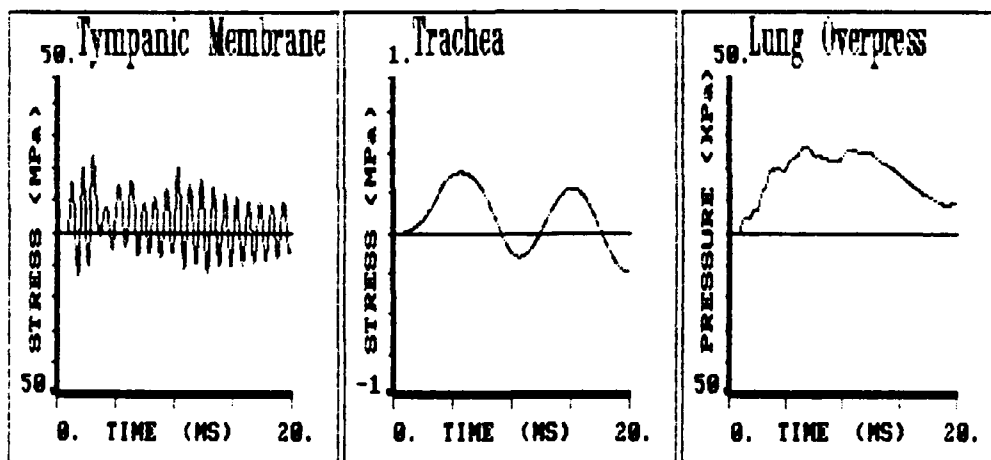
Model

Figure 11. 57 gm C-4 blast "S" free field sensor.

Field Data

Model

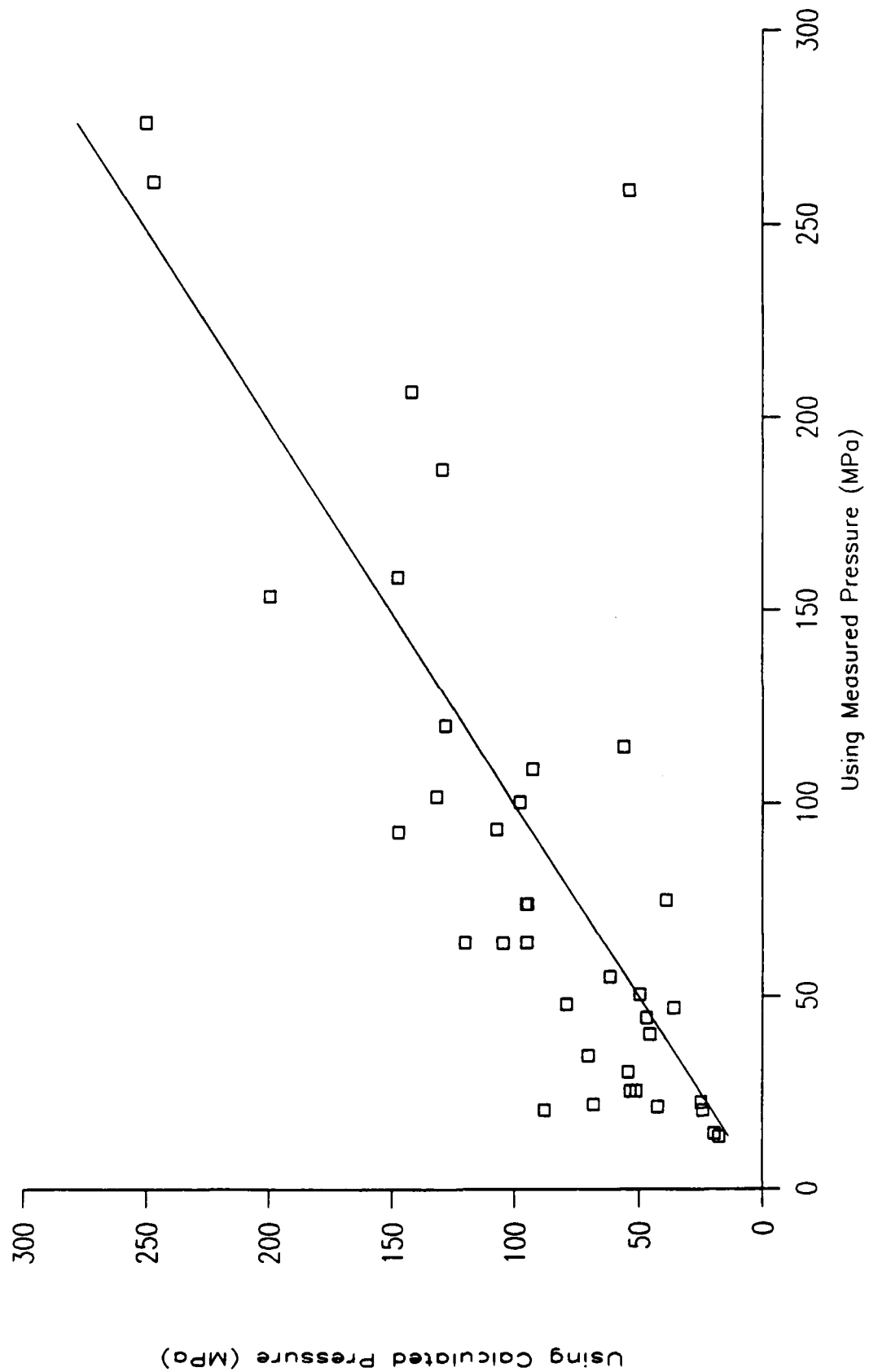Figure 12.   2/13/87 blast Lambdroid face-on sensor.
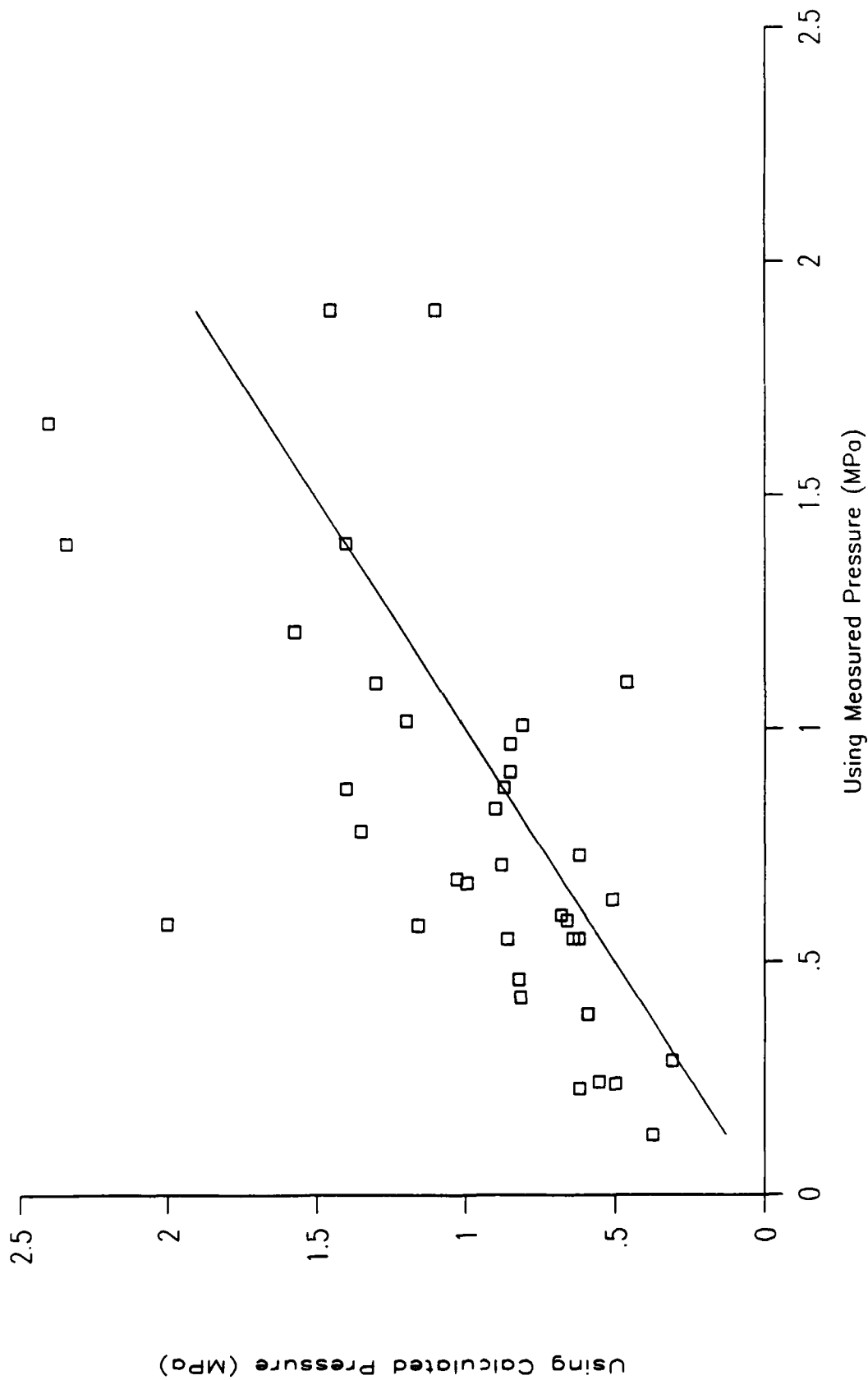
Figure 13. Tympanic stress.
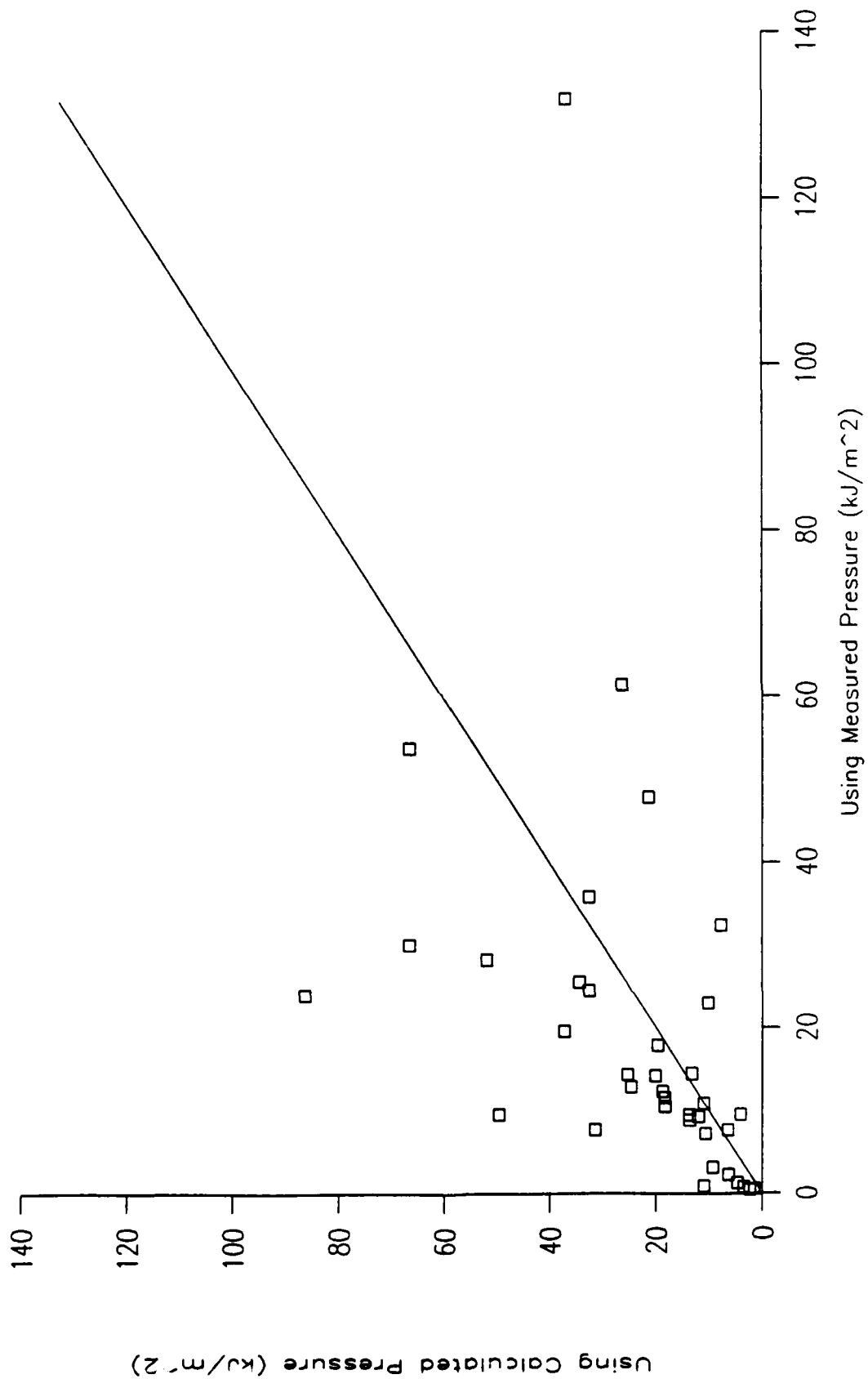
Figure 14. URT stress.

Figure 15. Work done on lung.

5-6

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